CHAPTER 8.1

Sedimentation Equipment

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Sedimentation equipment is more commonly known as *thickeners* and *clarifiers* within the minerals industry, although other terms such as *subsiders* and *settlers* are also used. A wide variety of sedimentation equipment designs is available to the minerals industry. Selection and sizing of the proper piece of equipment depends on the process objectives. Details of the design of the equipment can vary not only with process objectives but also with site location and topography, material specific gravity and particle size, and availability of local building materials as well as plant operating philosophy.

The development of modern flocculants has led to high-rate and high-capacity designs that are optimized for their use. Modern flocculants have decreased the required sizing for sedimentation equipment by at least an order of magnitude. Flocculant is a significant operating cost and should be considered in an economic evaluation. Sometimes there is a trade-off between equipment size and required dosage, with higher throughput per unit area requiring a higher flocculant dosage, up to a point. It used to be that *conventional* meant that flocculant was not being used. Now it implies a mechanism that is not specifically designed for the optimal use of flocculant and is usually used as a reference point regarding the amount of risk in a design. In fact, past studies have shown that for this reason, flocculant dose in conventional thickeners can be at a similar rate to high-rate designs without real benefit. Therefore, a well-designed high-rate thickener should operate more efficiently and with lower risk than a larger well-designed conventional thickener using flocculant.

In the minerals industry, sedimentation equipment is ubiquitous. The most common applications in base metals involve thickening of tailings and concentrates. In alumina, nickel laterite, uranium, gold, and some of the other leach circuits, countercurrent decantation (CCD) is a fundamental part of the process, using as many as eight thickeners in series. Other common applications include clarification of plant discharge water, process water treatment, leach liquor clarification, removal of precipitates, pre-leach, and grind thickening.

There are three general types of thickener rake drive mechanism: bridge-mounted, center-column mounted, and traction drives. Bridge-mounted drives are centered on a bridge that spans the thickener, with a shaft attached to the rakes. Because of the bridge span, there is an upper limit on the size of machine this design can be economically applied to, generally around 40–50 m in diameter depending on the type of thickener.

Center-column drives are used on larger thickeners (or small ones without lifts) and are mounted on a center column that typically also supports an access bridge that spans one half of the tank. The shorter bridge is a relatively light structure, required for operating and maintenance access; the reduced weight compensates for the addition of the column and the use of a cage around the column to drive the rakes. These can be economical starting at about 35 m in diameter and are currently available up to a diameter of 130 m.

Traction thickeners use a peripheral drive mounted on one (or two) of the rake arms. These units can develop very high torques but do not have lift capabilities and are sensitive to environmental conditions regarding contact between the drive wheel and the rail or traction surface. In mineral processing plants, these are usually only considered for applications typically over 100 m in diameter.

Most thickener designs use center underflow outlets, with the floor slope determined by the type of thickener and, more correctly, the yield stress of the thickened slurry. In operation and as material is removed, thickened slurry flows by gravity toward the center of the tank, assisted by the rakes. In low slurry yield stress applications such as clarifiers, conventional, and many high-rate thickeners, floor slopes between 1:12 and 2:12 are common. Large-diameter machines often use a dual-slope design, with an inner slope of 2:12 and an outer slope of ½:12 or 1:12, to avoid making the machine excessively deep. As thickened slurry yield stress increases because of material behavior, as in the case of high-compression and paste thickeners, floor slope increases to aid slurry transport, and raking

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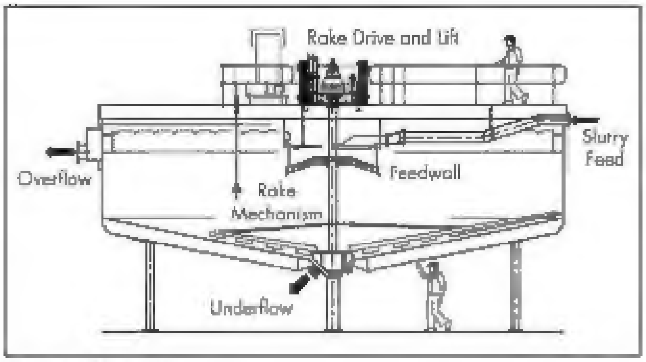
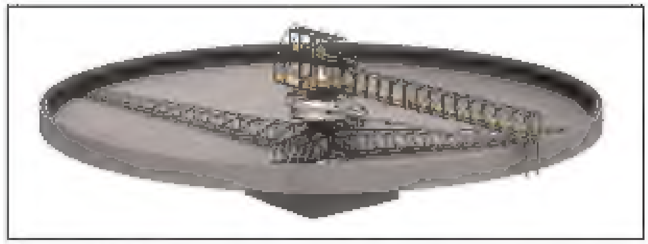


Courtesy of Outotec
Figure 1 Typical thickener with elevated tank



Courtesy of Outotec
Figure 2 Typical center-column thickener with on-ground concrete tank

Courtesy of Outotec
Figure 3 Typical full-span bridge thickener with elevated steel tank

becomes critically important. Even some high-rate thickener applications, such as uranium yellowcake and magnetite, use steeper slopes such as 3:12. High-compression and paste thickeners typically use floor slopes of 3:12 and up to 1:1.

The tank sidewall depth varies between 1.8 m in small-diameter thickeners to about 3.6 m in larger-diameter conventional and high-rate thickeners. For high-compression and paste thickener sidewalls, between 4 and 12 m are utilized to achieve solids compression in the bed and increase the mud retention time. In determining sidewall depth, both process and mechanical considerations are factors in design. A freeboard of 150–300 mm is usually used on both the tank and feedwell. The center outlet is typically either a center discharge drum or a 45-degree cone on bridge-type thickeners or a trench on center-column thickeners. Either requires a scraper assembly attached to the rake structure to keep the material moving. A generalized thickener is shown in Figure 1 showing the major structures and process connections for feed slurry, overflow liquor, and underflow slurry. Figures 2 and 3 are models of typical center-column and bridge-mounted thickeners, respectively.

THICKENER COMPONENTS

In addition to overall tank design, thickener components include feed systems, flocculants, rakes, and launders.

Feed Systems

Thickeners and clarifiers are typically fed in the top center and use a feedwell to condition the feed stream and promote solids settling. The feedwell is also the most common point for flocculant addition. Properly designing the feed system, including the feedwell and flocculant-addition location to maximize the effectiveness of flocculation, can have great impact on thickener sizing and performance. It is not uncommon for poorly operating feed systems to exhibit lower underflow density, poor overflow clarity, high flocculant consumption, and even raking problems in the full-scale thickener operation.

When optimizing thickener performance, design of the feed system should consider slurry properties from upstream processes. Excessive aeration, high slurry velocity, or excessively low slurry velocity entering a thickener feed system will often create poor performance from the thickener. Design factors to consider include

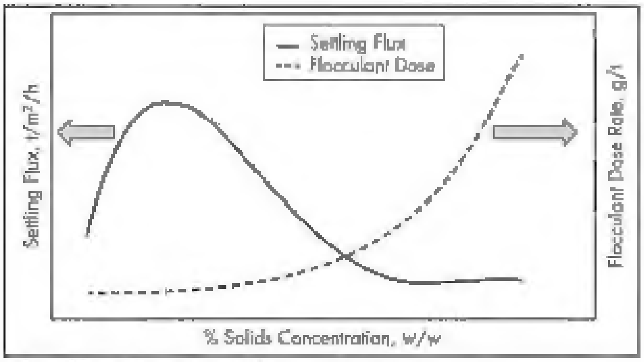
- Reduction in slurry aeration through improved upstream piping design and plant layout;
- Inclusion of thickener feed tanks to allow slurry deaeration, especially in the case of flotation concentrates; and
- Inclusion of velocity break tanks to slow down high-velocity launder flow.

To summarize, the feed system in a modern thickener has the following functions:

- Promotes deaeration of the incoming slurry
- Dissipates excess incoming slurry energy
- Effectively mixes flocculant and slurry dilution water (if required)
- Prevents feed slurry short-circuiting
- Promotes aggregate growth and even distribution of aggregates into the thickener tank for sedimentation

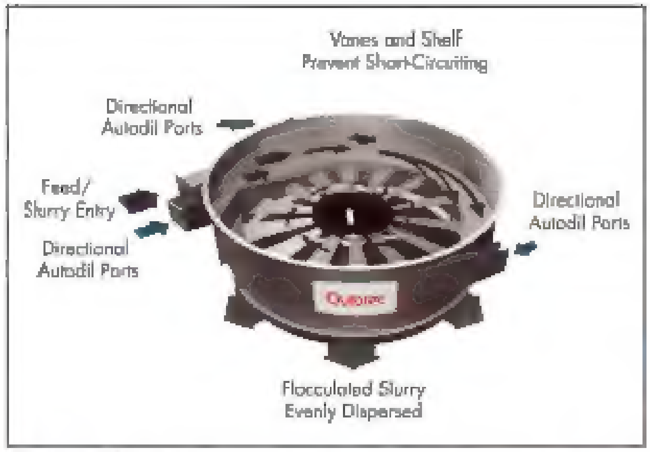
The feed slurry concentration for optimum flocculation and most economic thickener size is not necessarily the slurry concentration reporting to the thickener from the upstream process. Quite often, the feed slurry requires dilution prior to addition of flocculant to achieve best flocculation and thickening performance. This effect is presented in Figure 4. This figure shows a maximum in the settling flux at a relatively low solids concentration. The settling flux is the amount of solids settling through a given area, which is the product of the solids settling rate and the concentration. The optimal concentration depends on the characteristics of the feed solids. Very fine solids may need to be diluted to <5 wt % whereas the maximum flux may occur at 15–25 wt % for a coarse grind tails. For clarification, the feed slurry may be too dilute and may benefit from increased concentration by recycling underflow slurry back to the feed slurry. This is discussed in the "Solids Contact Clarifiers" section.

Also apparent from Figure 4 is the increasing flocculant dose rate (in grams per metric ton of dry solids) required as



Adapted from Schoenbrunn and Laros 2002

Figure 4 Feed solids concentration, settling flux, and flocculent demand



Courtesy of Outotec

Figure 5 Outotec Vane Feedwell with directional auto-dilution

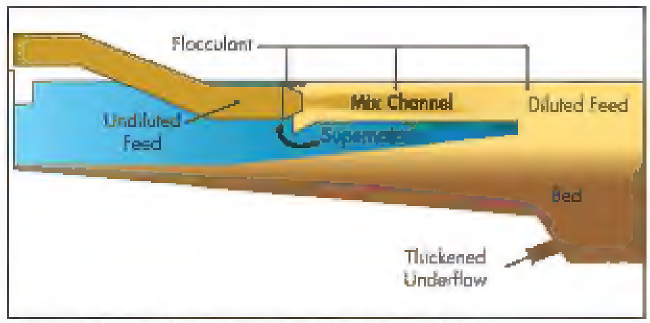


Figure 6 FLSmidth E-Duc self-diluting feedwell

solids density increases. Modern thickener feed systems use feed slurry dilution to both maximize solids settling rate and minimize flocculant dosage.

Many methods of feed dilution have been used since the advent of synthetic flocculants. Pumping of overflow liquor into the feed slurry from the overflow launder or directly from the top of the thickener with submersible pumps is quite common. This method requires a pump, which can be quite large and expensive in cases where large quantities of dilution are required. Early dilution methods without external pumping used slots or holes cut into the feedwell to draw dilution liquor into the feed slurry because of the density differential between the feed stream and the clarified liquor. These early types of feedwells are often referred to as Cross-type feedwells, as Harry Cross (1963) developed one of the first units.

Modern feedwells that include density-driven dilution systems and focus on energy dissipation include the Outotec Vane Feedwell shown in Figure 5. The Vane Feedwell uses dilution ports in the feedwell shell to direct dilution water from the thickener clarified zone into the feed slurry. The feedwell features a closed bottom design and is divided into upper and lower zones by a shelf and vanes. The upper zone mixes the feed stream, dilution water, and flocculant. The lower zone promotes aggregate growth and distributes the flocculated slurry evenly into the thickener for settling (Triglavcanin 2008).

An alternative method of dilution is to place an eductor or jet pump in the feed line to dilute, flocculate, and mix the slurry prior to entering the feedwell. The degree of dilution can be designed into the eductor through the geometry of the eductor and the driving head of the feed slurry through the eductor. This type of design is distinguished by the FLSmidth E-Volute feedwell that features the E-Duc dilution system. An example of this is shown in Figure 6.

Forced-feed dilution systems are also used in some applications. These typically consist of an electrically driven low-head/high-volume pump system in the top of the thickener to force dilution water into the feedwell. These may be required when operational process conditions do not allow effective use of the more simple density or flow-driven systems as described earlier. Two such systems include the Outotec Turbodil and FLSmidth P-Duc.

Flocculants

In a mineral suspension, there is usually a wide difference in particle size. Some particles may be large enough to settle out quickly, while very fine particles may not settle at all. The rate of settling of any given particle is dependent on its size, its density relative to that of the suspending medium, the viscosity of the medium, and the interactive forces between this and other suspended particles.

In mining applications, destabilization of the particle suspension is commonly achieved through polymer flocculation. Flocculation increases particle settling rate by agglomerating them into larger aggregates and is fundamental in the application of high-rate thickener design and operation. Typical polymer charges for mineral applications range from nonionic to highly anionic and can be applied over a wide range of pH and temperatures for most mineral slurries (Figure 7).

Flocculants are available in powder and liquid forms, both of which are made into solutions prior to dosing into the slurry entering a thickener. Solutions from powders are commonly made to 0.25–0.5% w/v concentration, whereas solutions from emulsion-type polymers are typically made to 1% w/v. This primary solution is made in dedicated polymer preparation plants, which can be fully or semiautomated.

Prior to dosing into the feed slurry, secondary dilution of the flocculant is recommended to a final concentration between 0.01% and 0.025% w/v. This increases mixing efficiency into the slurry and minimizes flocculant consumption. Care must be taken, however, with diluted flocculant solutions, as they are shear sensitive. Excess shear reduces polymer effectiveness because of molecule breakage, so secondary dilution of

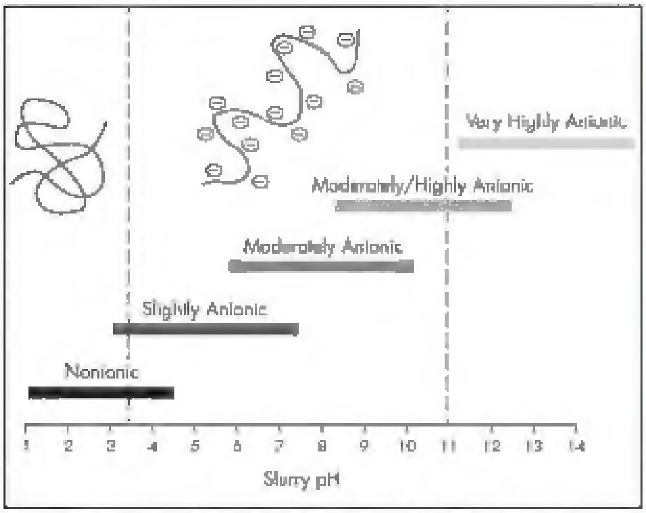


Figure 7 Common flocculent types in mineral applications

Courtesy of Outotec

Figure 8 Low-profile raking mechanism

primary solutions is best performed just prior to the dosing points in the thickener.

Flocculant is commonly dosed in multiple stages into dilute slurry. For most thickener applications, addition is performed in the feedwell of the thickener in multiple locations, ensuring good contact and mixing of the flocculant solution with the slurry particles. In some cases, a partial dose of the flocculant is also dosed upstream of the feed system or in the feed pipe. In all cases, flocculant addition is best done into dilute slurry to enhance mixing and to minimize flocculant consumption.

Thickener original equipment manufacturers include the flocculant dosing point design as part of the thickener scope of supply. Particle mixing and settling in feed systems makes the optimum placement and distribution of flocculant challenging, and some adjustment of dosing points is often required after initial start-up.

Rakes

Most thickeners use a set of arms that move through the pulp to help thicken the pulp and assist even movement of the thickened material to the underflow outlet. These typically have blades set at 30–45 degrees to the tangent of motion to push the solids toward the outlet. The rake arms must be strong enough to transmit the torque needed to push the solids toward the thickener discharge.

In most high-rate and conventional thickeners, most slurry flow toward the central discharge is by gravity. In this case, rakes assist and maintain even flow and solids distribution in the bottom of the thickener. In paste thickeners, slurry yield stress increases, and the slurry resistance to flow increases. In these applications, rake design and raking capacity become increasingly important to prevent thickener shutdown and to maintain performance targets.

Rake mechanisms are usually designed for specific process applications. Processes that produce a heavy scale buildup on the rakes, such as alumina refining, require a rake containing a minimum of steel surface area. Rakes for magnetite thickening may have spikes attached to the blades such that heavily thickened magnetite can be resuspended. Some rakes are of a streamlined low-profile design to help reduce the torque on the rake structure (Figure 8). Rakes may have pickets or thixo posts (posts to distance the blades from the rake arms) attached to them for processes in sticky or high yield stress applications. In general, rake design is ideally process dependent but must also meet the requirements of torque and deflection.

Rake Drives

The rake drive provides driving force (torque) to move the rake arms and blades against the resistance of the thickened solids. The drive also provides the vertical support for the rotating elements. Bridge-type thickeners can use spur gear, worm gear, planetary, or other commercial reducer drives. Column-mounted thickeners almost always use spur gear drives.

Rake design varies between manufacturers, with safety factors commonly between 1.0 and 1.5 times the 100% torque rating of the drive. It is therefore common for two or more levels of overload protection to be designed into the drive to prevent torque overloads and associated rake damage. Reliability is a critical issue with the drive, as failure frequently means digging out the thickener. Key drive elements are hardened steel gears, large precision bearings, oil bath lubrication, accurate torque measurement, and strong housings.

Torque descriptions used by thickener manufacturers include peak torque, design torque, maximum operating torque, normal operating torque, duty-rated torque, American Gear Manufacturers Association 20-year torque, cutout torque, and so forth (AGMA 2001-C95). This is partly due to the relationship of torque to gear life, where gears last a very long time at low torque, but exponentially shorter as the torque increases. It is important that equivalent design standards are used when comparing different thickeners, as drive life and operability can vary greatly.

There are two methods of motive power for drives: electric motors or hydraulic power packs. Hydraulic drives offer features such as soft starts, variable speed, torque indication by hydraulic pressure, low-speed hydraulic motors, excellent torque sharing on multiple pinion drives, and pressure relief as an overload protection. The downsides are low efficiency, higher cost, maintenance, and the added complexity of another system. Similar features are now available for electric drives using electric variable-frequency drives. Electric drive motors are relatively simple and can use mechanical, load cell type, or electronic load-sensing torque measurement and protection.

Table 1 Standard duties

Duty	Examples	K Factor
Light	River or lake water clarification, metal hydroxides, brine clarification	1–4
Standard	Magnesium oxide, lime softening, brine softening	5–9
Heavy	Flotation tails (copper, lead, zinc, nickel), iron tails, coal tails, flotation concentrates (coal, copper, zinc, nickel, or lead), clay, titanium oxide, gold tails, phosphate tails	20–40
Extra heavy	Uranium countercurrent decantation, iron ore concentrate, iron pellet feed, titanium ilmenite, coarse tailings	40–60

Adapted from Schoenbrunn and Laros 2002

Rake drive sizing is dependent on the application, with variables such as particle size distribution, specific gravity, flocculant use, solids loading, rake design, and design underflow concentration affecting the selection. Because the torque is related to the thickener diameter by a square power function, a K factor is usually used to refer to a drive size independent of diameter, where torque = K × D (diameter)^2. Depending on units used, the formula for rake torque is

$$\text{torque} = 14.6 \times K \times D^2$$

where

torque = maximum operating torque, N·m
D = diameter of thickener, m

Table 1 shows typical values for standard duties, covering clarifiers as well as conventional and high-rate thickeners. However, the selection of an appropriate K factor should also consider the preceding variables and may need to be significantly different from those shown in Table 1. For example, very high underflow densities may dictate a K factor to be an order of magnitude higher.

When selecting the drive K factor for high-compression and paste thickeners, the consolidated slurry yield stress becomes a dominating design criteria. For those applications, K factors between 150 and 400 are typically required.

Rake speed for thickeners is typically determined by tip speed—the velocity of the outer tip of the rake arm. For most thickeners, this may be 8–12 m/min and is driven by solids area loading. For clarifiers and low solid loading rates, this number is lower.

Rake Lifts

Rake lifts are used to protect the drive from high torque with a typical vertical lift between 300 and 600 mm. These can be used with either bridge or center-column designs and can be hydraulically or electrically actuated. A typical bridge-mounted thickener drive and rake lift is shown in Figure 9.

Traction-type drives are generally not compatible with rake lifts, although some have been supplied using the cable-type design described next. Lifts are typically powered by a separate motor from the drive and must be designed for precise control. Lifts can prevent shutdown of the machine in plant-upset conditions, for example, when large amounts of coarse material are encountered or, more generally, when the thickened material reaches a very high yield stress. Their use in minerals applications is fairly ubiquitous, although there are many applications that do not need a lift or where extra torque would make a lift unnecessary.

Courtesy of Outotec

Figure 9 Single planetary rake drive with hydraulic rake lift

Lifts have been used to aid in storing material, especially mineral concentrates, in a thickener. The rake is lifted allowing thickened concentrate to accumulate below the rake. The rake is then slowly driven into the dense concentrate to evacuate the thickener. This technique is not commonly used; however, it illustrates the need for the rakes and supporting structure, such as the bridge or column, to be designed to accommodate a downward force from the lift in addition to upward forces.

Cable-type lift designs use an arm hinged at the center connection and are supported and towed by cables, so that the arms can pivot upward when an obstruction or high torque is encountered. The advantages of this design include a streamlined arm design and low cost. The main disadvantages are the lack of positive control of the arm position and the inability of the rakes to lift significantly in the center, where the heaviest accumulations are usually found.

Drive Power

Thickener rake drive power is a function of torque and rake speed. In a mineral processing plant, thickener drive power consumption is a relatively low value compared to other unit operations in comminution, beneficiation, pumping, and filtration.

Rake drive power can be estimated by the formula

$$\text{power (kW)} = \frac{0.105 \times \text{speed} \times \text{torque}}{\text{efficiency}}$$

where

speed = rake speed, rpm
torque = rake torque, kN·m
efficiency = 0–1; mechanical efficiency of the drive system, which can be 0.9 for electric drives and 0.7 for hydraulic drives

From the preceding formula, the installed rake drive power can be determined from the maximum operating torque of the rake drive. Additional power is added for rake lift and is typically an incremental increase of rake drive power depending on rake lift capacity and may be between 20% and 30% of the drive power.

Actual operating power consumption can therefore be estimated as approximately 15%–20% of the total installed drive power in a correctly sized thickener drive.

Effluent Launders

Most thickeners use a peripheral effluent launder to collect the clarified overflow and bring it to a single or double discharge point. The effluent should uniformly flow into the launders around the periphery of the tank and should not be backflooded into the thickener. V-notch weirs are often provided to assist in distributing the effluent around the periphery of the tank. The weirs can be built into the tank launder or can be a separate, adjustable element. Froth baffles can be located at the liquid level just inboard of the launder and are used to prevent floating material from getting directly to the launder. Flotation concentrate thickeners are almost always provided with froth baffles and often with some method of froth management such as water sprays and rotating booms.

Other methods of handling effluent include radial launders, single-point discharge, and bustle pipes. Radial launders are often used on solids contact clarifiers to help distribute the effluent removal evenly over the surface of the clarifier. Conversely, some applications can use a simple single-point discharge nozzle and still have acceptable overflow clarity. Bustle pipes are often used where liquor storage is desired at the top of the tank or the tank liquor level is variable, using submerged pipes with orifices to distribute the effluent discharge.

The size, slope, and number of discharge points of a launder are determined using hydraulic flow equations developed by the thickener manufacturers.

Tank Design

There are many possible tank styles that can be used, with attendant trade-offs. Most mineral applications require good access to the underflow piping, and it is usually good practice to locate underflow pumps near the thickener underflow outlet. This leads to the need for either elevated tanks or underflow access tunnels. Because of the complexity, cost, and safety issues with underflow tunnels, elevated tanks (Figure 10) are generally preferred for small- to medium-size thickeners, up to about 45 m in diameter, although larger elevated tanks to 65 m have been built. Other benefits of elevated tanks are storage space underneath, unhindered pump access, and ease of leak detection and repair. Elevated steel tanks can be of welded or bolted design. Bolted designs can offer significant installation savings by reducing site labor requirements for erection, although transport of resulting larger tank sections to remote sites can increase shipping costs. Steel tank materials offer various choices to suit process conditions from mild steel through stainless steel and duplex materials.

On-ground tanks do not require the structural steel needed for elevated tanks, and so they are generally preferred for applications where underflow pipe access is not critical, as well as for large-diameter thickeners and clarifiers, generally 50-m diameter and above (Figure 11). If the process allows the underflow pipe to be buried to the edge of the thickener without high risk of blockages, an on-ground tank can be significantly less expensive. As a result, on-ground tanks are fairly common in clarification and water treatment applications.

Courtesy of Outotec

Figure 10 Elevated thickener tank with bolted steel construction

Within the realm of on-ground tank design, there are many construction methods available using steel or concrete. *Anchor channel construction* refers to a steel channel embedded in a concrete footing at the wall, with the steel shell welded or bolted to the anchor channel. With this construction, the floor can be concrete, membrane, or fill. The other method of construction for a steel wall tank is to use a steel floor on a compacted foundation.

For concrete wall tanks, the floor can be concrete, membrane, or fill. Fill material used in construction should be engineered, properly sourced, placed, compacted, and inspected as part of the overall tank construction. Various linings, covers, and insulation can be applied to suit the process. The use of clay liners alone is limited because of groundwater contamination concerns. However, clay layers can be used effectively in combination with a variety of membranes in an engineered system.

SEDIMENTATION EQUIPMENT DESIGNS

Equipment designs for clarifiers and thickeners, including high-rate, high-compression, and paste thickeners.

Clarifiers

Standard clarifiers are often used for water and wastewater applications. These units usually have relatively low K factors and, hence, light mechanisms because the amount of raking, particle size, and solids density are usually on the light end of the spectrum. Rake lifts are frequently not needed. In general, clarifiers are very similar in appearance to thickeners. The feedwell is generally larger in volume and the tank depth greater, with tank walls typically 3 m high or more. This is done to provide more time for feed slurry flocculation in the feedwell, slower velocities exiting the feedwell, and a longer liquor detention time in the clarifier. These features are necessary to achieve optimum overflow liquor clarity.

Classic clarifier hydraulic loadings start at about 1 $m^3/h/m^2$ and typically go up as high as 6 $m^3/h/m^2$ for some solids contact clarifiers with optimal feed solids. Nominal sizing at 2.4 $m^3/h/m^2$ is a good starting point for many applications. These numbers consider using coagulants or flocculants,

Courtesy of Outotec

Figure 11 On-ground tank with concrete floor and bolted steel walls

which greatly aid the particle settling rate. Chemical addition is almost always used in clarification applications because of its effectiveness at flocculating very fine particles and increasing the effluent overflow clarity.

Solids Contact Clarifiers

This equipment is designed to internally or externally recirculate solids and to promote particle contact and flocculation in the reaction well or to enhance solids precipitation or hardness reduction. This can be done externally by pumping a portion of the underflow back to the feedwell. The same thing can be accomplished internally using a draft tube and a turbine to draw solids from the bottom of the clarifier tank.

The design philosophy for solids contact clarifiers is to maximize the size and concentration of aggregates in the reaction zone by having the pumping capability to suspend a high concentration of solids. Using the draft tube and turbine, solids are recirculated centrally and directly above the tank floor. The heavier particles necessary for improved settling velocities are mixed with the incoming feed to allow particle contact and aggregate growth. Flocculation and recirculation are accomplished symmetrically within the reaction well for the most efficient use of reactor volume and turbine energy.

A large feedwell provides the required detention time and allows precipitation to take place prior to the slurry entering the clarification zone. Chemical addition is introduced into the recirculation zone in the presence of previously formed precipitated solids prior to passing through the turbine for optimum mixing and flocculation.

Typical hydraulic loadings for solids contact clarifiers are 2.4–4.8 $m^3/h/m^2$, upward to 12–24 $m^3/h/m^2$ in some steel mill wastewater clarification applications.

Inclined Plate Clarifiers

Inclined plate clarifiers use plates to increase the effective settling area in a small tank. The plates are set at a 45–60-degree angle to allow settled solids to slough off. The plates are typically stacked with 50-mm spacing, although this can be varied for the application. The effective area is the sum of the horizontal projections of the plate areas. They can be supplied with either rakes or steep cone bottoms and are often available as packaged units in a square or rectangular configuration. These units are very effective at putting a lot of area in a small tank but are susceptible to solids buildup and plugging.

Conventional Thickeners

There are some applications for which polymer is either not needed or may adversely affect downstream processing, and hence it is not used. For these situations, a conventional thickener is all that is required. However, there are many conventional thickeners that use flocculant to improve overflow clarity, handle a higher tonnage, or aid in achieving the desired underflow density. These units are often fairly simple, although relatively sophisticated mechanisms are used for particular applications. Because of the relatively large size, they are somewhat forgiving in operation and may have the storage capacity to absorb some plant upsets without affecting downstream operations if sufficient torque and raking capacity is installed.

Typical features include a drive and rakes, a relatively open and shallow feedwell, and a bridge to support the feed pipe or launder and allow center access. The drive size is dependent on the application. Conventional thickeners can be either bridge, center-column, or traction design. Early thickeners (prior to 1970) mostly fall into this category.

High-Rate Thickeners

With the advent of synthetic flocculant, the terms *high rate* and *high capacity* emerged as a type of thickener, as the throughput rates for the now flocculated feed slurries were considerably higher than for unflocculated slurries. These terms now generally refer to designs optimized for use with flocculants, although further improvements on earlier optimized designs are evident as the technology has continued to evolve and improve. Thickener size or throughput is highly dependent on flocculant dose and feed slurry concentration, as presented in Figure 4. Consequently, most high-rate thickeners commonly use feed dilution systems when the incoming feed density is above the value for optimum settling. The size of these thickeners can be somewhat governed by capital and the primary operating cost of flocculant. A smaller thickener will have a lower installed cost but may be more costly in the long run because of a higher overall flocculant cost, and vice versa.

High-rate thickeners are commonly small- to medium-sized bridge-type thickeners up to 50 m in diameter, although large center-column thickeners processing very high tonnage can also fall into this category. Flocculation is required, and feed slurry dilution systems are often needed for optimal performance. This is the most common type of thickener in the minerals industry today. Grinding, tailings, leach, pre-leach, CCD, and concentrate thickeners often fall into this category. Because of the wide range of applications, solids loading rates vary considerably and in free settling applications can go to 1.5 $t/m^2/h$ or higher. Hydraulic capacity must also be considered in the design with values typically up to 6 $m^3/h/m^2$ and at the higher end to around 12 $m^3/h/m^2$. Table 2 contains typical sizing parameters for common high-rate thickener applications.

Common features include a self-diluting feedwell, heavy-duty drive, streamlined rake arms, and large effluent launders and underflow outlets. Because of relatively high solids loading rates, instrumentation and automated control systems are required on high-rate thickener applications to maintain steady-state operation and avoid downtime caused by rake *bogging*. Some examples of high-rate thickeners are shown in Figures 12 and 13.

High-Rate Rakeless Thickeners

This relatively new class of sedimentation equipment uses a deep tank and steep-bottom cone to achieve the underflow

Table 2 High-rate thickener sizing

Application	% Solids, w/w		Solids Loading Rate, t/m²/h†	Liquid Loading Rate, m³/h/m²‡	K Factor
	Feed*	Underflow			
Alumina, Bayer process					
Red mud clarifiers (settlers)	3–4	25–35	0.1–0.3	3.0–6.0	175–200§
Red mud washers	6–8	30–40	0.7–1.0	6.0–10.0	175–200§
Red mud final washers	6–8	35–45	0.7–1.0	6.0–10.0	175–200§
Hydrate	2–8	30–50	0.05–0.2	1.5–2.5	125–150§
Brine purification	—	—	0.01–0.02	0.5–1.2	10–25
Coal					
Coal tailings	0.5–6.0	25–40	0.1–0.4	1.0–6.0	20–30
Clean coal fines	4.0–7.0	30–40	0.2–0.4	2.0–5.0	75–150
Dense media (magnetite)	10–15	60–70	0.3–0.5	3.0–6.0	35–40
Flue dust					
Blast furnace	0.1–2.0	40–60	0.05–0.15	1.0–2.5	20–30
Base metal concentrates					
Copper concentrate	10–20	50–70	0.15–0.25	1.0–2.5	35–40
Zinc/lead concentrate	10–15	50–70	0.15–0.2	1.0–2.0	35–40
Nickel concentrate	10–15	50–65	0.15–0.25	1.0–2.5	35–40
Flotation tailings	10–15	45–65	0.15–1.00	1.5–6.5	30–45
Iron ore					
Concentrate	15–25	60–75	0.4–1.5	2.0–6.0	35–50
Tailings	1–10	50–65	0.2–0.6	2.0–6.0	20–35
Gold					
Countercurrent decantation (CCD)	10–15	40–55	0.3–0.8	3.0–6.0	25–35
Tailings	10–15	50–65	0.3–1.0	3.0–6.0	30–35
Copper CCD	10–15	55–65	0.5–0.8	3.0–6.0	35–40
Nickel laterite CCD	5–10	35–50	0.3–0.5	4.0–6.0	35–50
Molybdenum concentrate	8–10	35–55	0.05–0.15	0.5–1.5	30–40
Mineral sands slime	2–4	20–35	0.1–0.25	4.0–7.0	20–30
Platinum					
Concentrate	7–12	50–60	0.1–0.2	1.5–3.5	35–40
Tailings	8–15	45–55	0.15–0.5	3.0–6.0	30–35
Uranium					
Acid-leached ore	10–15	45–65	0.30–0.60	3.0–6.0	30–35
Uranium precipitate	1–2	10–30	0.01–0.05	0.5–2.5	20–25

Adapted from Schoenbrunn and Laros 2002
* Feed density for flocculation, which may include dilution.
† Solids loading rate = feed rate (t/h)/tank cross-sectional area (m²).
‡ Liquid loading rate = feed rate (m³/h)/tank cross-sectional area (m²).
§ K factor based on scale load.

density while eliminating the rake and rake drive. The design is based on maximizing throughput rate in a small diameter while achieving good underflow density and overflow clarity. Flocculant is always used, and feed dilution is usually built into the design.

Because these units have a very low residence time, startup and shutdown are quick, typically requiring only about 30 minutes to reach steady-state operation. They are operated as continuous process equipment and cannot be used for storage. The lack of a rake mechanism and smaller diameter makes these units a generally lower-cost alternative to rake thickeners. Operation is relatively simple; however in some applications, control can be unstable and plugging of the internals is sometimes a risk. It has also been demonstrated that in many applications, rakeless thickeners are unable to achieve the same consistently high density as properly configured raked thickeners. These limitations and the relatively small unit capacity has seen rakeless thickeners penetrate only niche applications in thickening. Current examples are the FLSmidth Eimco E-Cat clarifier-thickener and the Delkor Ultrasep ultra-high-rate thickener. A diagram of the internal flow pattern of an E-Cat clarifier-thickener is shown in Figure 14.

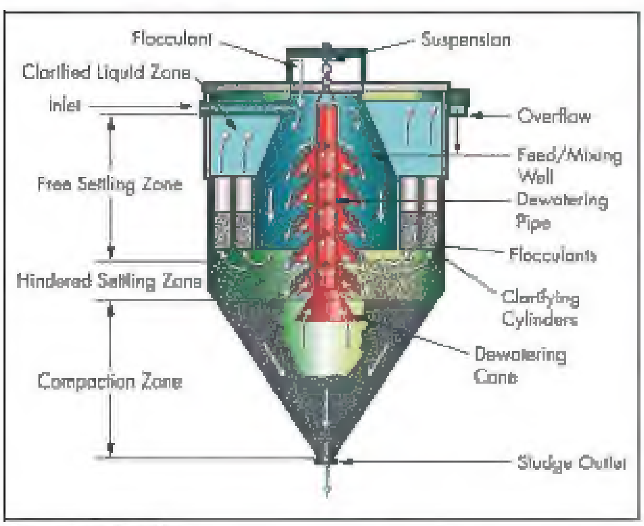
High-Compression or High-Density Thickeners

This technology is an extension of high-rate thickening, utilizing a deeper mud bed to augment the available compression forces in the bed, thus achieving higher underflow density compared to high-rate thickeners. High-compression thickeners typically add 1–3 m in sidewall depth to a high-rate design to aid in increasing the underflow density. Deeper mud beds increase the mud compressive force, which, combined with raking, increases underflow density.

As slurry yield stress increases with density, these machines use steeper floor slopes to aid slurry transport and require significantly more installed rake torque (two to five times) than high-rate machines. Mechanism design is also optimized for dewatering in deeper solids beds and may commonly feature dewatering pickets and thixo posts on the rake blades. Similar

Courtesy of Outotec
Figure 12 High-rate thickener, 65-m diameter

Courtesy of Outotec
Figure 13 High-rate thickener CCD circuit



Courtesy of FLSmidth
Figure 14 E-Cat clarifier/thickener showing the internal flow patterns

to high-rate thickeners, high-compression or high-density thickeners require good instrumentation and process control systems to consistently achieve high-density underflow.

Paste and Deep Cone Thickeners

Today's paste thickeners originated from work done by the British Coal Board in the 1960s, utilizing steep-bottom tanks without rakes to produce underflows with very high solids contents. The goal of the work was to produce a material that could be put on a conveyor, and while this was not achieved consistently, very thick material could be produced (Klepper et al. 1998). Further development by Alcan in the alumina industry (Emmett et al. 1992) eventually led to commercialization of this technology outside alumina, with applications ranging from high-efficiency CCD washers to underground paste disposal and wet stacking of surface tailings. The FLSmidth Deep Cone paste thickener and Outotec paste thickener are examples of this design. In some applications, it is possible to produce material at the limits of pumpability with these units. An example of a paste thickener installation is shown in Figure 15.

Although underflow with the consistency of paste can be achieved by high-rate, high-rate rakeless, or high-compression machines, paste thickeners are currently the best technology for achieving maximum underflow densities utilizing sedimentation equipment alone. These units typically use very deep mud beds to take maximum advantage of mud compressive forces for dewatering and provide sufficient time for the mud to dewater to a paste consistency. The tank height-to-diameter ratio is frequently 1:1 or higher. Because of the high underflow yield stress, mechanism torques can be 5–10 times higher than high-rate machines on similar materials. Floor slope is also increased to between 30 and 45 degrees to aid in material transport. Rake mechanisms are specifically designed for dewatering in deep beds and to positively transport thickened slurry to the central discharge without causing rotation of the solids within the tank. Some suppliers may incorporate additional elements into the mechanism design to prevent rotation of agglomerated solids masses sometimes known as *donuts*.

Applications include surface tailings disposal by wet stacking, underground paste backfill, CCD, and pre-leach applications. In paste thickening, instrumentation and control

Courtesy of Yara
Figure 15 Paste thickener, 30-m diameter with 40-degree floor slope

systems are critical to achieve the required high-density underflow and to avoid equipment downtime.

INSTRUMENTATION AND PROCESS CONTROL IN RAKED THICKENERS

Although early and conventional thickeners used very little instrumentation and process control, the advent of high-rate designs and widespread use of flocculation to enhance settling has made process control essential for consistent thickener performance and to reduce costly machine downtime. To some degree, advances in thickener mechanical and process design have been outpacing the availability of reliable instrumentation and process control systems. Many thickeners are installed with traditional single-loop proportional integral controllers through plant distributed control systems. In many cases, these can be tuned to achieve control over steady-state operations. Process upsets coupled with slow and complex process dynamics often lead to poor control results. Many thickeners are then operated in a manual or semimanual operating mode.

Instrumentation and control strategies should be implemented based on several criteria: Application, thickener type, and process output priorities are key factors in deciding on a control strategy. The availability and capacity of resources to maintain sometimes complex control systems should also be considered.

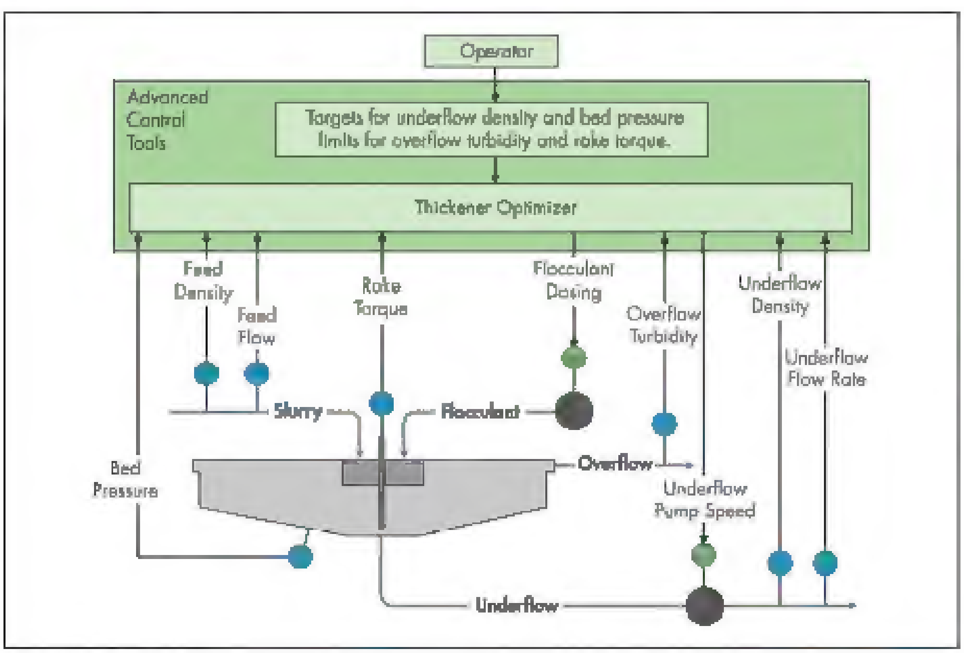
New approaches to controlling thickeners using expert control systems or multivariable model predictive control (MPC) have shown advantages in overcoming the limitations of single-loop controllers (Kosonen et al. 2017). This application integrates highly interactive controls of solids inventory, underflow density, and overflow clarity into a single controller. The MPC is able to take changes in the incoming flow into account, deal with process constraints, and support prioritization between control variables. The results from this control system include increased stability and reduced variability around the desired process set points. An example of a thickener control schematic is shown in Figure 16.

TEST WORK AND SCALE-UP METHODS

A method widely used for conventional thickener sizing using static cylinder laboratory-scale tests was developed by Coe and Clevenger (1916). They identified four settling zones in a settling solid–liquid suspension, namely, clear water zone, initial or free settling zone, transition zone, and compression zone. By a series of batch settling tests, using a typical slurry sample, the limiting solids flux (solids settling rate per unit area) was established, which was then used for scale-up on a full-sized thickener. To allow for potential dynamic effects and material variations, it was usual to use a safety factor in scale-up (usually 20% or 25%). This method was simplified further by Kynch (1952), who applied a mathematical method to demonstrate that the limiting solids flux could be determined from a single batch test.

With the advent of high-rate thickener technology in the 1970s, a laboratory-scale dynamic test-work approach was used, both as a means of providing accurate sizing and a demonstration of the high-rate concept. Since the first thickeners of this type were put into service by Enviro-Clear, a dynamic test method has been adopted and further developed by many manufacturers including Supaflo (now Outotec), FLSmidth, Delkor, and others.

On the laboratory scale, a small thickener, typically 100 mm in diameter (Figure 17), is used, fitted out with all the elements of a full-scale thickener, that is, feed pipe, feedwell/flocculation tank, slurry deflector plate, a set of small rotating rakes, and an underflow offtake. This unit is fed from a mixing tank containing a suspension of a typical plant sample. The feed rate is calculated to present to the test unit a solids flux, measured in metric tons per square meter per hour, appropriate to the application. Flocculant is added prior to or at the feedwell, and the flocculated slurry is introduced into the thickener settling zone via the feedwell deflector plate



Courtesy of Outotec

Figure 16 Optimizing control for thickeners

Courtesy of Outotec

Figure 17 Dynamic test thickener, 100 mm

Courtesy of Outotec

Figure 18 Pilot thickener, 1-m diameter

or similar. The rakes are rotated and underflow withdrawal started once a compression zone of settled solids is formed. This continues until steady-state operation is achieved, at which time the underflow and overflow are sampled and measured for density and clarity, respectively.

This test is repeated with a series of solids flux rates and flocculant addition rates until a data set is built up showing the relationship between the preceding variables. It is then possible to determine the appropriate flux rate and flocculant dosage to achieve the desired underflow density and overflow clarity directly from the data. Because the laboratory-scale thickener has a limited compression zone depth (usually no more than 250 mm), the flux rate selected on the basis of a required underflow density is regarded as conservative, and no safety factor is applied for scale-up to the full scale.

Test programs on pilot-scale thickeners have been used by some high-rate thickener manufacturers for situations in which large variations in feed conditions are anticipated, or where process conditions cannot be accurately simulated in the laboratory. Generally, pilot test work is carried out in the plant location and feed to the unit is taken directly from the appropriate plant process stream. The methods of data collection and scale-up are similar to the dynamic bench scale. However, because of the set-up time and need to cover a range of process conditions, pilot-scale test programs usually run to days or weeks and require significant personnel resources rather than one technician in a single day, as is the case with a typical laboratory test series. A typical 1-m-diameter pilot unit is shown in Figure 18.

TROUBLESHOOTING OPERATING THICKENERS AND CLARIFIERS

Table 3 is a list, by no means exhaustive, of common operating problems, together with some typical solutions.

FEED DEAERATION FOR FROTH CONCENTRATE THICKENERS

Flotation concentrates, which usually contain a high degree of air entrainment as a froth, present a particular challenge for thickener designers. The entrained air attaches as small bubbles to solids particles and causes solids to float to the surface of the thickener, resulting in dirty overflow and concentrate loss.

The conventional approach to this problem was to allow extra area in the thickener and include a large feed tank before the thickener to allow some of the entrained air to escape. These are still recommended design practices; however, at least one manufacturer uses a feed tank design that applies a centrifugal force to the incoming feed to accelerate the removal of entrained air. Even large amounts of froth in the feed have been shown to be removed by this type of feed tank (e.g., Outotec FrothBuster), and consequently, good thickener performance can be achieved without resorting to oversized feed tanks and thickeners. Alternatively, water sprays and froth booms can be effective for control.

MAJOR FACTORS INFLUENCING THICKENER DESIGN

The following issues can influence thickener design:

- Process requirements for the overflow liquor quality and underflow slurry density. These determine the thickener type, size, drive, and mechanism design.
- The quantity of solids to be handled. Usually expressed as weight of dry solids per unit area per hour, this typically determines the size and number of units.
- Hydraulic loading is the volume of feed divided by the cross-sectional area of the thickener and is typically expressed as rise rate in cubic meters per hour per square meter.
- The amount of material larger than 250 µm (+60 mesh) in the feed. This affects tank bottom slope, drive, and strength of mechanism. It may also require a rake-lifting device.
- Specific gravity of the solids. The greater the specific gravity, the more likely a stronger drive and mechanism will be required.
- Particle size, concentration, and settling characteristics will determine the feed system design, including the need for feed dilution.
- Feed, overflow, and underflow systems must be capable of handling additional material when other thickeners are out of service.

Table 3 Operating problems and solutions

Problem	Causes	Solutions
Low underflow density	• Can be caused by feeding a higher-than-design rate of solids to the thickener • Insufficient flocculant dosage • Inadequate flocculant mixing with the feed solids • Change in grind to a finer particle size • Low bed level caused by suboptimal thickener process control • Insufficient feed dilution	• Reduce solids feed rate • Increase flocculant dosage • Ensure correct flocculant secondary dilution • Increase solids inventory—bed level or bed mass • Move or optimize flocculant dosing locations • Change flocculant type • Ensure adequate feed dilution
Poor overflow clarity	• Sliming thickener: This occurs when the solid–liquid interface rises to the overflow weir, and slurry at a solids concentration similar to the thickener feed overflows the weir. • Overflow is murky, but not in a sliming condition: A portion of the feed solids is probably not being flocculated adequately.	• The usual solution to sliming is to increase flocculant dosage, increase underflow removal rate, or both. If necessary, the feed should be stopped until the interface drops back to normal. • Increasing feed dilution should be considered. • Increase flocculant dosage. • A different flocculant may be more effective, or a combination of inorganic settling aids (e.g., lime, iron chloride, alum) and synthetic flocculants (using laboratory-scale tests to identify the best flocculent combination is recommended). • If the problem persists, it could be a result of suboptimal mixing in the flocculation zone, which would imply a change to the flocculent/feed mixing chamber configuration.
High rake torque	• High torque with high-density underflow	• Mud load or solids inventory in the thickener needs to be reduced by increasing underflow pumping rate, reducing flocculant dosage, or both.
	• High torque with low-density underflow: This usually indicates short-circuiting of partially thickened material to the underflow and is commonly caused by a mass of agglomerated solids adhering to and rotating with the rake arms. The condition is variously referred to as a d , i ld , or solids mass.	• The usual cause is overflocculation of feed for a significant period. It is often difficult to remove without draining the thickener, although sometimes raising and lowering the rakes in a rapid sequence may move the mass. Flocculant dose rate should be reduced to a correct level for flocculation.

Adapted from Schoenbrunn and Laros 2002

- Underflow material characteristics may require special rake construction such as blades located a distance below the rake arms on posts (thixo posts).
- Scale buildup tendency of feed slurry may require special arms and drive (e.g., alumina applications).
- An operating requirement to accumulate solids for defined periods of time will require a special mechanism design, as it is not a normal operating procedure.
- Froth control or removal may require sprays, froth baffles, or skimmers.
- Slurry properties (pH, chlorides, etc.) will determine materials of construction for the wetted parts (tank and mechanism).
- Slurry temperature, vapors, gases, and so forth, may require covered and/or insulated tanks with attendant seals.
- Soil conditions and groundwater elevation affect foundation design and may determine tank and mechanism type.
- Climatic conditions may require special considerations, such as enclosures around the drive, tank insulation, and instrumentation.

CONCLUSIONS

A range of sedimentation equipment designs are available for various applications and process objectives. Utilizing the proper design for an application can make the difference between a smooth operating process and continual problems that prevent a plant from realizing its potential. Taking the time in the project planning stage to make sure the correct design is being used can make for a successful project.

REFERENCES

AGMA 2001-C95. 1995. *Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth*. Alexandria, VA: American Gear Manufacturers Association.

Coe, H.S., and Clevenger, G.H. 1916. Methods for determining the capacity of slime settling tanks. *Trans. AIME* 55:356–385.

Cross, H. 1963. A new approach to the design and operation of thickeners. *J. S. Afr. Inst. Min. Metall.* 63(7):271.

Emmett, R.C., Laros, T.J., and Paulson, K.A. 1992. Recent developments in solid/liquid separation technology in the alumina industry. In *Light Metals 1992*. Edited by E.R. Cutshall. Warrendale, PA: The Minerals, Metals & Materials Society. pp. 87–90.

Klepper, R., Laros, T., and Schoenbrunn, F. 1998. Deep paste thickening systems. In *Minefill '98: Proceedings of the Sixth International Symposium on Mining with Backfill*. Edited by M. Bloss. Melbourne, Victoria: Australasian Institute of Mining and Metallurgy.

Kosonen, M., Kauvosaari, S., Gao, S., and Henriksson, B. 2017. Performance optimisation of paste thickening. In *Proceedings of the 20th International Seminar on Paste and Thickened Tailings*. Edited by A. Wu and R. Jewell. Beijing, China: University of Science and Technology.

Kynch, G.J. 1952. A theory of sedimentation. *Trans. Faraday Soc.* 48:166–176.

Schoenbrunn, F., and Laros, T. 2002. Design features and types of sedimentation equipment. In *Mineral Processing Plant Design, Practice, and Control*. Edited by A.L. Mular, D.N. Halbe, and D.J. Barratt. Littleton, CO: SME.

Triglavcanin, R. 2008. The heart of thickener performance. In *Paste 2008: Proceedings of the 11th International Seminar on Paste and Thickened Tailings*. Edited by A. Fourie. Nedlands, Western Australia: Australian Centre for Geomechanics.